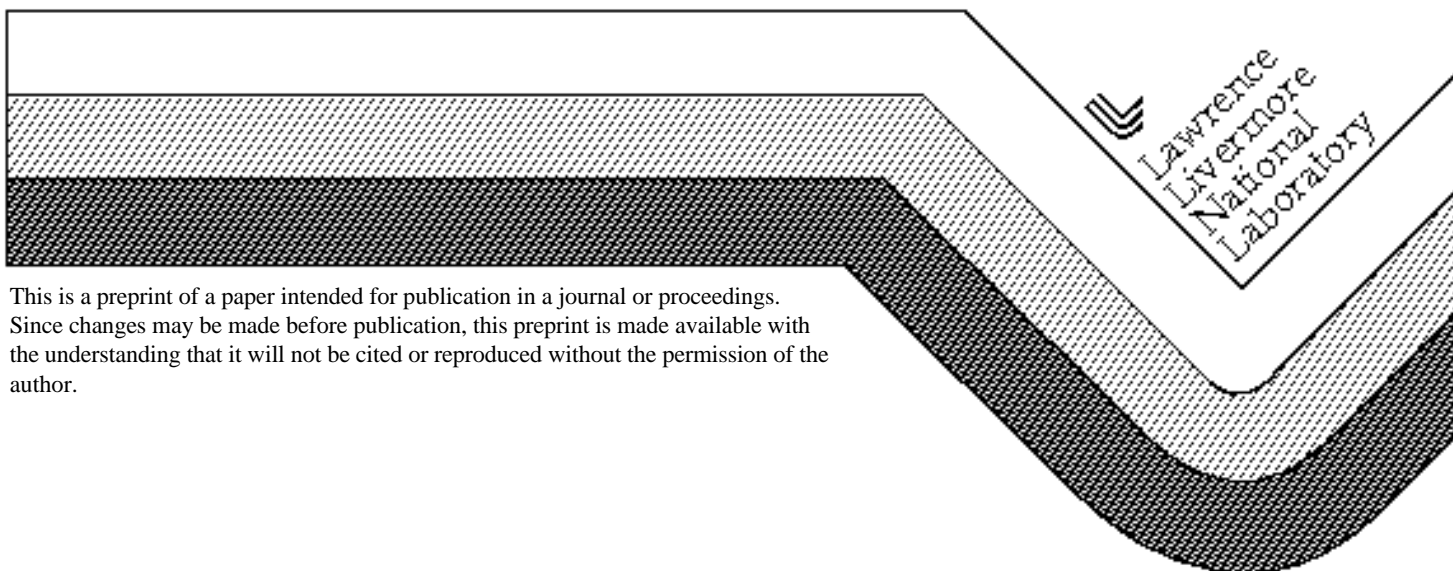


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This paper was prepared for submittal to the  
44th Annual Meeting of the International Symposium on  
Optical Science, Engineering, and Instrumentation  
Denver, Colorado  
July 19-23, 1999

July 15, 1999



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# A Novel Condenser for EUV Lithography Ring-Field Projection Optics

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## ABSTRACT

A condenser for a ring-field extreme ultra-violet (EUV) projection lithography camera is presented. The condenser consists of a gently undulating mirror, that we refer to as a ripple plate, and which is illuminated by a collimated beam at grazing incidence. The light is incident along the ripples rather than across them, so that the incident beam is reflected onto a cone and subsequently focused on to the arc of the ring field. A quasi-stationary illumination is achieved, since any one field point receives light from points on the ripples, which are distributed throughout the condenser pupil. The design concept can easily be applied to illuminate projection cameras with various ring-field and numerical aperture specifications. Ray-tracing results are presented of a condenser for a 0.25 NA EUV projection camera.

**Keywords:** illuminator, condenser, grazing-incidence reflection, EUV projection lithography, x-ray optics

## 1. INTRODUCTION

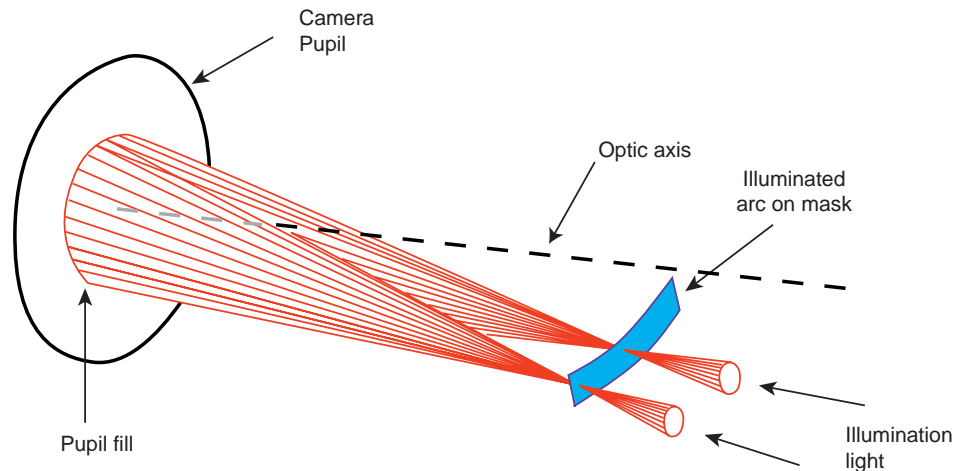
The properties of an image of a non-luminous object depend strongly on how the object is illuminated, even if the imaging system is aberration free and diffraction limited. In lithography, where it is extremely important that the image characteristics are invariant across the imaging field, the condenser optical system is a critical component. Designing a condenser for an EUV (11–14 nm wavelength) ring-field projection lithography camera has been found to be a considerable challenge, due to the difficulty in mapping a small circular source on to a long, narrow ring-field arc, whilst maintaining the desired angular distribution of illumination at each field point in that arc. In Addition, the condenser must be all-reflective and must gather as much light as possible from the source, in order to reduce exposure times to an economical level.

Scanning ring-field EUV lithographic projection optics are designed so that aberrations are well corrected over a narrow annulus centred on the optical axis.<sup>1,2</sup> A sector of this annulus is used for printing, which is achieved by synchronously scanning the mask (in the object plane) and wafer (in the image plane) at constant velocities to sweep out the required area. Several condenser concepts and designs have been developed to illuminate ring fields with light from a small circular source. One approach is based on a critical-Köhler condenser (see Sec. 3), in which the source is imaged to the mask in the narrow dimension of the ring-field arc (the critical dimension), and the condenser collector pupil is imaged to the mask in the long arc dimension (the Köhler dimension).<sup>3,4</sup> This scheme, however, leads to a narrow and long angular distribution of the illumination, whereas a disc “pupil fill” is desired, as is outlined in Sec. 2. A critical-Köhler condenser is being fabricated for the Engineering Test Stand,<sup>2</sup> a 0.1 numerical aperture EUV lithography system being developed by Lawrence Berkeley, Lawrence Livermore, and Sandia National Laboratories in the USA.<sup>3,5</sup> The narrow and long pupil fill is overcome by segmenting the collector into six channels, which are individually manipulated to give the required arc intensity with an angular distribution consisting of six lines to approximate the required disc. The design is very efficient in terms of light collected, and gives very uniform intensity across the field, but it does require 19 optical elements and probably would not meet the demands of future, higher numerical aperture systems. A similar approach is taken in a design with multifaceted mirrors.<sup>6,7</sup> In this case, a more uniform pupil fill can be achieved due to the greater number of channels. Yet another critical-Köhler approach fills in the pupil by using a diffuser, located near the mask plane, to scatter light into the desired angular distribution.<sup>7</sup>

A fundamentally different approach, used in the condenser design presented in this paper, builds upon the critical condenser, which images the source onto the mask plane (in both dimensions), and images the condenser pupil onto the camera entrance pupil. A small circular source is imaged to the mask to give a circular patch of illumination the size of the narrow arc dimension. The desired arc intensity pattern can be generated at the mask by using a mirror in the condenser pupil, to modify the angular distribution of light there. This *angular* distribution in the pupil is mapped to a *spatial* distribution at the mask plane. In addition, in order to ensure a stationary pupil fill, the light that reaches a particular field point must be reflected from points distributed throughout the condenser pupil—since these reflection points are imaged into the camera pupil, giving the pupil fill. A condenser concept based on this approach uses an array of cylindrical mirrors, to give a one-dimensional angular distribution of light in the condenser pupil.<sup>8</sup> This is then transformed into an arc by 45° reflection from a large aspheric mirror into an arc. In this work, an arc angular distribution is achieved directly by grazing-incidence conical reflection, described in Sec. 4.1, from a mirror with slight undulations in one direction that we refer to as a ripple plate. This leads to a much higher throughput, and greater flexibility in the design. The ripple-plate condenser design principles are outlined in Sec. 4.2, and the ripple profile that produces uniform illumination intensity is derived in Sec. 4.3. To illustrate the design principles, a condenser is designed for a future 0.25 NA EUV projection lithography system. The performance of the condenser is simulated, and the results are given in Sec. 5.

## 2. ILLUMINATION REQUIREMENTS FOR LITHOGRAPHY

The criteria of an illumination system for ring-field projection optics are driven by the lithographic requirements of printing binary patterns with a high degree of process latitude and uniformity across the entire field, at a fast rate. These criteria are essentially a measure of the optical performance of the condenser, for example: shape and uniformity of the pupil fill; lack of any variation of illumination characteristics across the field (stationarity); telecentricity; EUV throughput; and compensation of camera errors. Of these, the pupil fill and stationarity are most important, since they encompass the main purpose of an illuminator: namely, providing illumination of the mask in a way that optimises its aerial image and minimises any variation of the printed image across the field. The EUV throughput must be maximised due to the economic need to minimise exposure times. In addition to these optical metrics, there are also those of the scalability to higher NA imaging systems, and the ease of manufacturability of the condenser.



**Figure 1.** The condenser must supply illumination such that all the light at each point of the illuminated part of the mask uniformly fills a central disc of the camera entrance pupil. From Murphy *et al.*<sup>7</sup>

**Pupil Fill:** The distribution of the illumination at the camera pupil, for a given field point, is known as the pupil fill of the condenser. This must usually be centred on the camera pupil, to give bright-field imaging. For binary amplitude objects, the contrast of images is usually optimised if the pupil fill is a disc smaller than the pupil itself. The ratio of the radii of the illumination disc to the pupil is called the partial coherence, or  $\sigma$ , of the illumination. The optimum value of  $\sigma$  varies between about 0.3 to 0.8, depending on the dominant frequency of the pattern.<sup>9</sup>

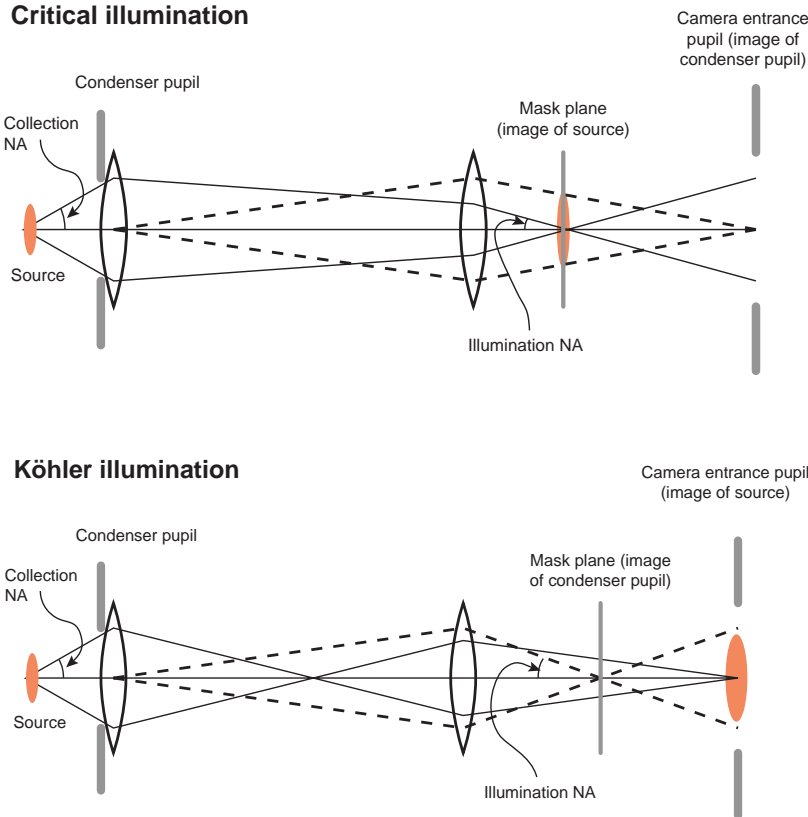
**Stationarity:** This means that the illumination intensity and pupil fill be the same for all field points, as illustrated in Fig. 1. Ring-field systems print images by synchronously scanning the mask and wafer at constant velocities. In this case the stationarity requirement need only be valid in the time-averaged sense. That is, a given point on the mask is printed on the wafer by scanning through the imaging field of the camera. The illumination intensity may vary along the point's trajectory across the field, as long as the scan-integrated intensity along that path is the same for all trajectories. In the same way, the pupil fill may vary along a given scan trajectory, as long as the scan-integrated fill is the same for all trajectories. In practice, some variation across the field, such as a 5 % variation in pupil fill location in the entrance pupil, may be tolerated.<sup>10</sup>

**Throughput:** The EUV power at the wafer is limited by the maximum power output of the EUV source, so as much light as possible must be collected from the source and used to illuminate only the required field at the mask plane. The efficiency of the condenser will obviously be greater with fewer optical elements, and better still if those elements operate at grazing-incidence rather than near-normal incidence. For EUV sources such as laser-produced plasmas and discharge lamps, the emission is usually over a large solid angle, as much as an entire hemisphere. With these sources the entrance NA of the condenser must be as large as possible. With a synchrotron source (bending magnet or insertion device) the emission is confined to a much smaller solid angle and the condenser entrance NA should match this emission to make efficient use of it. With all sources, however, the solid angle of collection is constrained by the étendue of the required illumination (see Sec. 3). The required illumination area and NA, along with the source size, constrain the maximum solid angle of collection that is achievable. In the case of ring-field systems illuminated by a plasma source there is a mismatch between the étendue of the source and the required illumination, primarily due to the disparity between the long thin ring field and the circularly symmetric source. A bending magnet synchrotron source, on the other hand, is better matched to the Köhler collection solid angle in that the emission is spread out in a fan. The étendue of synchrotron sources is usually much smaller than that required by the projection optics. This is an easier problem to solve than having an étendue which is too large, since the étendue can be increased by diffraction, scattering, and the use of various non-imaging optical elements.

### 3. CRITICAL AND KÖHLER ILLUMINATION

Stationary illuminators are one of two kinds: critical (also known as Abbe) and Köhler (see Fig. 2). These can also be combined in a hybrid illuminator that is critical in one transverse dimension and Köhler in the other. Critical illumination is when the source is imaged onto the illumination plane, and the condenser pupil is imaged onto the camera entrance pupil. The source is imaged by the collector lens. A field lens images the condenser pupil by redirecting the illumination of off-axis points back into the on-axis camera pupil. To illuminate a field of radius  $r_i$  with a source of radius  $r_s$  requires a magnification  $M = r_i/r_s$ . The illumination NA (i.e. the condenser exit NA, see Fig. 2) of  $\sin \theta_i$  is then achieved with a condenser collection NA of  $M \sin \theta_i$ . Note that the magnification, and hence the collection angle, is limited by how small the source can be made.

In Köhler illumination the condenser pupil is imaged onto the illumination plane, and the source is imaged onto the camera pupil. The source size then determines the illumination NA and the angular emission of the source determines how large a field can be illuminated. Köhler illumination is usually preferred in optical instruments such as microscopes and lithographic cameras because the illumination tends to be very uniform even if the intensity of the source is not spatially uniform. Illuminating a field of radius  $r_i$  from a source of radius  $r_s$  constrains the collection half-angle to be  $\theta_s = \theta_i r_i/r_s$ .



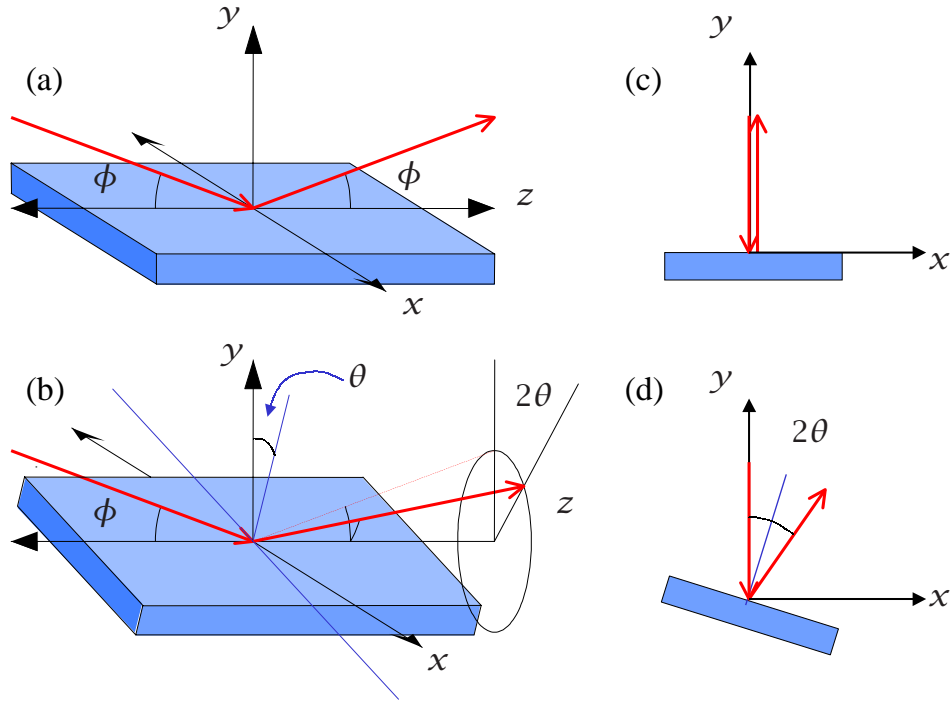
**Figure 2.** Schematic diagrams of possible layouts for critical illumination (above) and Köhler illumination (below). In EUV condensers mirrors take the place of lenses. After Sommargren and Seppala.<sup>11</sup>

A fundamental theorem which applies to all imaging systems is that the étendue (the volume in area-solid-angle phase space that the light occupies, or the product of the area and solid angle of the illumination) is an invariant of the system. Thus, the étendue at the illumination plane is equal to that at the pupil plane and equal to usable étendue of the source. Therefore, to satisfy the étendue requirements of the illumination (set by the required field and pupil fill of the camera) we require a source which has at least the same étendue. We find that a small circular plasma source, of the right size to match the étendue in the narrow dimension of the ring field, is very deficient in étendue in the long dimension. This is true for both critical and Köhler illumination, although the critical-Köhler combination will at least provide the arc intensity distribution (the étendue deficiency leads to a pupil fill that is too narrow in the arc's long dimension). In the ripple plate design, and other concepts reviewed earlier,<sup>5,7</sup> the étendue is effectively increased by redirecting the light to fill the pupil in a more uniform, although incomplete, fashion.

## 4. THE RIPPLE PLATE

### 4.1. Conical reflection

The central idea of the ripple plate condenser is to use a flat mirror with gentle corrugations in one direction. When collimated light illuminates the plate at an angle other than normal incidence it gets redirected onto an arc. The incident light must be aligned along the direction of the grooves of the ripple plate; that is, the component of the incident vector in the plane of the ripple plate must be parallel to the grooves. The effect is the geometrical analogue of conical diffraction from a diffraction grating, which occurs when the grating is illuminated in a similar manner.

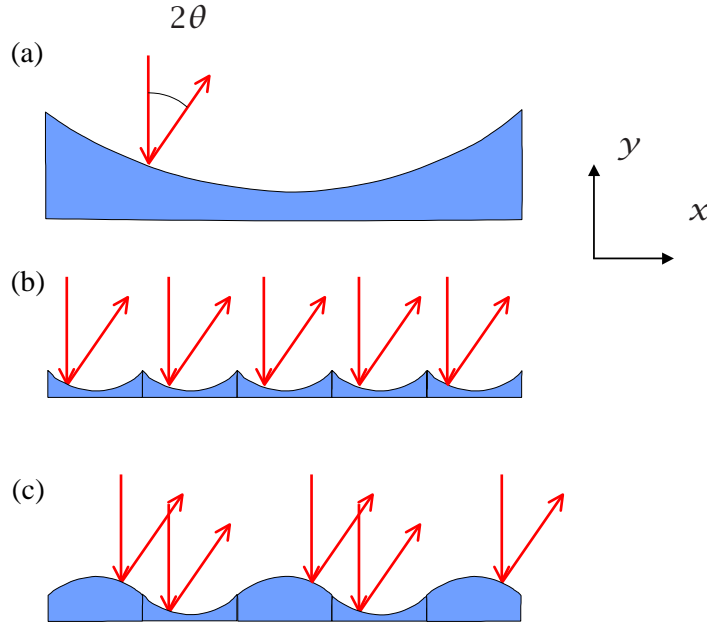


**Figure 3.** The reflected ray, from a plane mirror which has been rotated by an angle  $\theta$  about the  $z$ -axis, lies on a cone, at an azimuthal angle of  $2\theta$ . The apex half angle of the cone is equal to the incidence angle  $\phi$ .

Conical reflection will in fact occur for any mirror shape where the surface height does not vary in one direction—the direction parallel to the axis of the cone. To explain this, consider grazing-incidence reflection from a plane mirror. This is shown in Fig. 3 (a) for a ray incident at an angle  $\phi$ . For this discussion the origin is taken as the point of reflection. The included angle between the incident ray and the  $z$  axis is  $\phi$ . If, as shown in Fig. 3 (b), the mirror is rotated by some angle  $\theta$  about the  $z$  axis, then the angle of reflection changes but the included angle of the incident ray and the  $z$  axis remains the same (since the  $z$  axis of the mirror remains invariant under this rotation). The angle between the reflected ray and the  $z$  axis is of course equal to that between the incident ray and the  $z$  axis, i.e.  $\phi$ . Thus the reflected ray must lie somewhere on a cone, with an apex half-angle of  $\phi$ , and cone axis corresponding to the  $z$  axis. The position of the reflected ray on the arc can be determined by considering only the  $x$ - $y$  components of the rays, as shown in Fig. 3 (c) and (d), from which it is seen that the azimuthal angle of the reflected ray is  $2\theta$ . Although quite a feasible way to construct a condenser, it is not necessary that the mirror must physically rotate. We can see that any stationary mirror in which the slope in the  $x$  direction varies across the mirror, and remains constant in the  $z$  direction, will reflect rays into an arc. If the greatest slopes in the  $x$  direction are given by  $\pm \tan \theta$  then the azimuthal angle of the arc will vary between  $\pm 2\theta$ .

#### 4.2. Critical condenser based on conical reflection

One example of a mirror which is constant in slope in one dimension is a cylindrical mirror. A pencil beam of light incident on a cylindrical mirror along its axis will reflect onto the edge of a cone. However, the apex of the cone is at the point of reflection, which obviously differs for each point across the surface of the mirror. When the cylindrical mirror is illuminated by a broad collimated beam then the rays will be reflected onto different cones, each one with a different apex position. However, every cone has the same apex angle, so the distribution of *angles of reflection* will be an arc in  $\theta_x, \theta_y$  space. This distribution of angles can be transformed



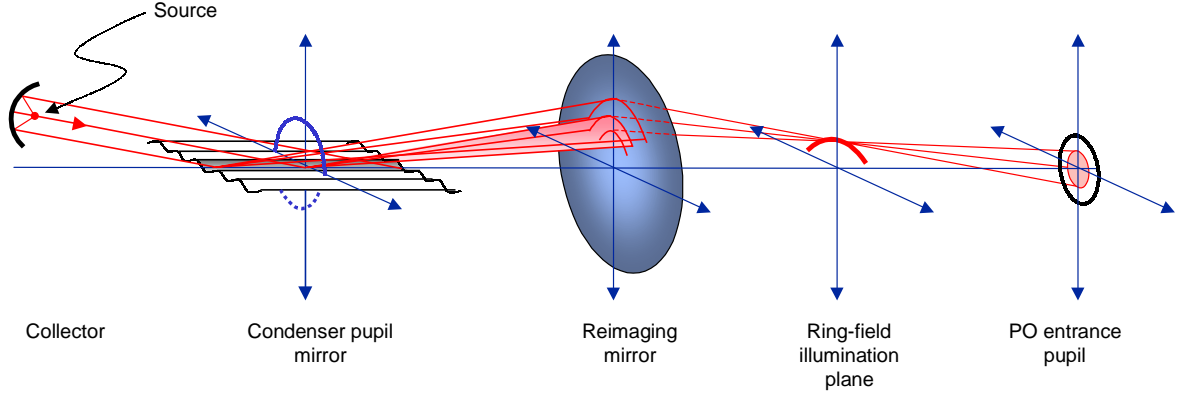
**Figure 4.** The condenser is arranged so that a particular pupil-mirror angle of reflection maps to a particular field point, and the position of reflection maps to a particular illumination angle at that field point. (a) For a cylindrical pupil mirror there is only one  $x$  position which will reflect rays to a particular field point, and thus the illumination at that point will be constrained to a single angle in the  $x$  direction. (b) More angles of illumination can be added by ensuring that particular slopes of the mirror occur at many positions over the mirror, which can be done by repeating a cylindrical mirror. (c) By alternating concave and convex cylinders, a surface is formed which is smooth and continuous.

into an actual arc intensity pattern at the back focal plane of a lens (all rays impinging a lens at a particular incidence angle are focused to a common point at the back focal plane of the lens) or, in this case, an imaging mirror. The lens or mirror also transforms positions into angles, so the incidence angle a ray makes on the arc depends on where on the cylindrical mirror reflection took place. That is, the cylindrical mirror is the pupil of the condenser, and the spherical mirror reimages that pupil into the entrance pupil of the projection optics. An illustration of such a condenser is shown in Fig. 5.

This is a Critical condenser, since an image of the source (albeit a highly aberrated image) is formed on the object plane, and the condenser pupil is imaged onto the projection optics entrance pupil. Although the condenser stop may be circular, the pupil fill for any one field point will not be the circular image of that stop. That is because light is directed to a particular field point only from points on the condenser mirror with a particular slope. In the case of the cylindrical mirror there is only one line at a constant value of  $x$  which satisfies that condition, as is illustrated in Fig. 4 (a). Thus, the pupil fill for any given field point on that arc will be limited to a narrow line instead of a solid circular fill.

A quasi-uniform pupil fill can be achieved by demanding that a particular slope is distributed across the face of the condenser pupil mirror. This can be done by reducing the radius of curvature of the cylindrical mirror and repeating it many times in the  $x$  direction, as shown in Fig. 4 (b). In this case the pupil fill for a particular field point will consist of a single line for each of the repeating cylinder units. At the intersection of adjacent cylinders, the gradient is discontinuous. Such a sharp point may be difficult to manufacture and may also lead to high-angle scattering. A smooth and continuous surface can be made by alternating concave and convex mirrors of equal but opposite curvatures, as shown in Fig. 4 (c). The convex mirrors have the same distribution of slopes as the concave mirrors. The only difference is that a particular slope occurs at a different





**Figure 5.** One implementation of a condenser utilising a ripple plate. The collector forms a broad collimated beam of light which reflects from the ripple plate. Only illumination on one period of the ripples is shown. A ray will be reflected onto the edge of a cone whose apex is at the point of reflection. The various arcs thus formed can be focused into one arc by a reimaging mirror (shown here schematically as a lens). The reimaging mirror also images the ripple plate (the condenser pupil) onto the entrance pupil of the projection optics. The reimaging mirror may be a near-normal sphere, or a rotationally-symmetric grazing-incidence mirror.

position in the convex and concave mirrors. For every period of the undulating mirror, a particular field point will receive light from two lines.

The full ripple-plate condenser is shown in Fig. 5. The required illumination intensity and angular distribution at the object plane are achieved with the one ripple plate mirror. This mirror has a distribution of slopes so that the distribution of reflected rays forms an arc in angular space. Any particular slope is distributed across the mirror in a quasi-uniform way (periodic, in this case). The reimaging mirror transforms ray directions (which are distributed in an arc) into positions at its back focal plane. The reimaging mirror also images the condenser pupil into the projection optics entrance pupil to give stationary illumination.

### 4.3. The functional form of the ripple plate

The ripple plate will reflect light into an arc, no matter what the height variation is in the  $x$  direction. The profile of the plate does determine the distribution of intensity on the arc, however. Since a particular slope on the ripple plate maps to a particular azimuthal point along the arc, the distribution of slopes determines the azimuthal distribution of intensity on the arc. Consider collimated light incident along a differential strip  $dx$  of the plate, where the gradient in the  $x$  direction is given by  $dy/dx = \tan \theta$  (see Fig. 6). The range of slopes in that differential strip is given by  $d\theta$ , so the light will be reflected into a differential sector on the arc of angle  $2d\theta$ , at an azimuthal position of  $2\theta$ . For a scanning ring-field projection camera, we require that the scan-integrated intensity be constant for all positions on the arc. Given a ring-field radius  $R$ , the differential sector on the arc will paint out a scanned strip of light of width  $2R \cos(2\theta)d\theta$ . We require that each scanned strip be of the same width (and hence yield the same scan integrated intensity), for a given strip width  $dx$  on the plate. That is,

$$\cos 2\theta \frac{d\theta}{dx} = \text{constant} = c, \quad (1)$$

for which the solution is

$$\theta = \frac{1}{2} \arcsin \frac{2x}{c}. \quad (2)$$



## 5. A CONDENSER DESIGN FOR 0.25 NA PROJECTION OPTICS

A ripple-plate condenser design has been made using CodeV,<sup>12</sup> and is shown in Fig. 7. The layout is similar to that shown in Fig. 5, with the imaging lens replaced by a grazing-incidence toroidal mirror. In this design no attempt was made to constrain the overall size of the condenser or optimise the distance from the source to the collector. The condenser was designed to provide illumination for a 0.25 NA six-mirror projection optics system designed by Russell Hudyma of LLNL, from a 0.25 mm-diameter laser-produced plasma source. This camera has a ring-field radius of 120 mm at the mask, a ring-field width of 8 mm, a demagnification of 4 $\times$ , and the entrance pupil is located 680 mm from the mask. The condenser design provides an illumination NA of 0.044, giving a fill of  $\sigma = 0.7$ .

The curvatures of the toroid are set so that the focal lengths for both transverse dimensions are equal. The meridional radius of the toroid is twice the ring-field width, so that parallel rays with  $x$ - $y$  components travelling in a particular direction from the ripple plate (cf. Fig. 4) will be focused to a common point on the curved focal surface, corresponding to the ring field. The angle of incidence on the toroid must be the same as that required for the illumination angle at the mask. For this six mirror design, the incidence angle is 10°. We can now find what the sagittal radius of the toroid must be, from the relations<sup>13</sup>

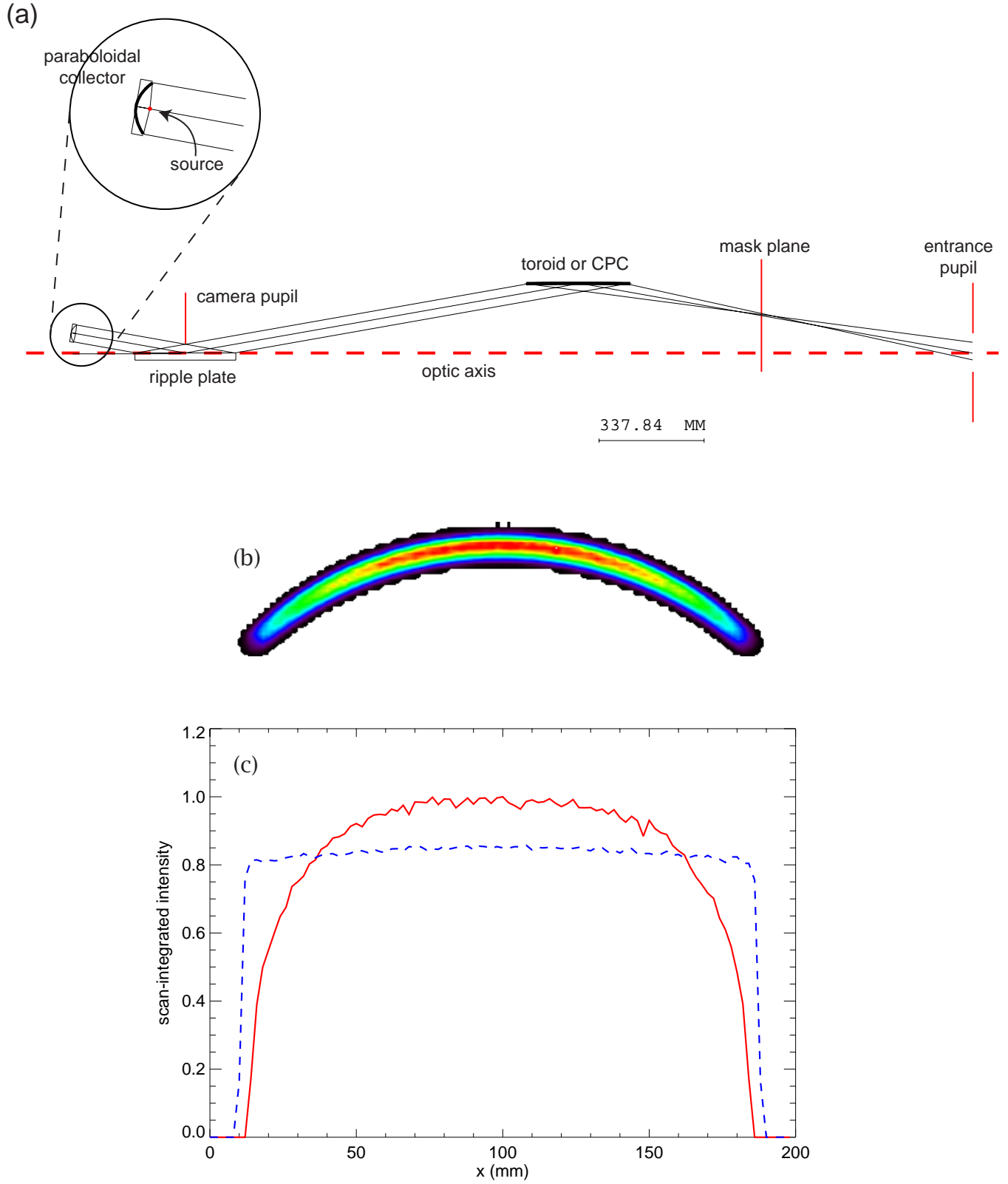
$$f_m = (R_m/2) \sin \phi, \quad f_s = R_s / (2 \sin \phi), \quad (7)$$

where  $f_m$  and  $f_s$  are the meridional and sagittal focal lengths respectively,  $R_m$  and  $R_s$  are the radii, and  $\phi$  is the grazing angle of incidence. Therefore, the focal lengths (equal to the distance between the toroid and mask plane) must be 680 mm and the meridional radius is 7959 mm. The angle of incidence from the ripple plate is also 10°, so the distance from the ripple plate to toroid is twice the toroid focal length.

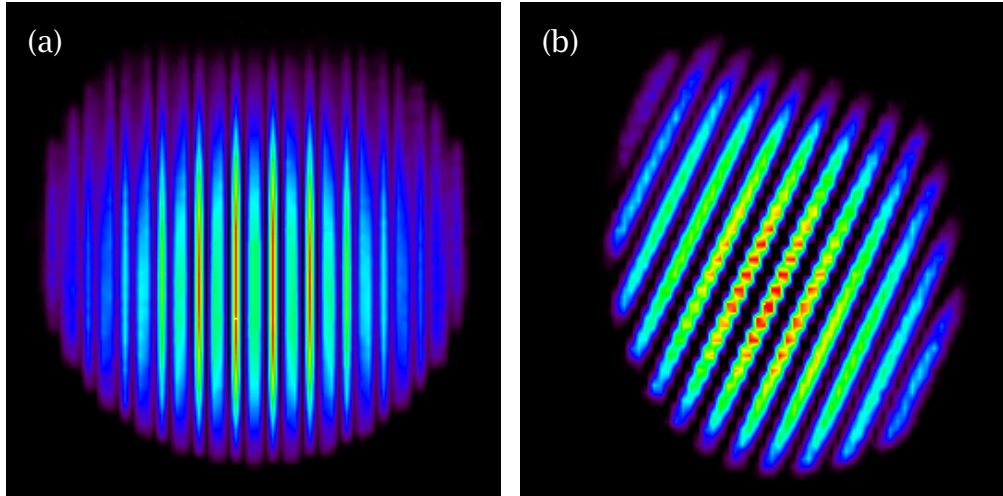
The size of the image of the source in the meridional plane at the mask is larger than the geometrical magnification of the condenser, due to aberrations of the toroid. These aberrations can be significantly improved by using a compound parabolic concentrator<sup>14</sup> (CPC) instead. Such a surface is generated by placing a parabola tilted by the 10° angle of incidence, and displaced from the optic axis so that its focus lies on the ring-field radius. The surface of revolution is formed by rotating about the optic axis. The curvature of the parabola is adjusted so that the slope of the parabola is zero (parallel to the optic axis) at a point twice the distance from the optic axis than the ring-field. The surface is then a higher-order correction to the toroid.

The specification for field width in a scanning system is 25 mm at the printed wafer, or 100 mm at the mask for a demagnification of 4 $\times$ . For this example we illuminate an even wider field of 170 mm, or a 90° sector of the 120 mm radius arc. The 90° arc is easily achieved with the ripple plate. From Eqn. (6) this requires a peak-valley amplitude of the ripple 0.158 times the period. That is, an amplitude of 792  $\mu\text{m}$  for a 5 mm period. The intensity profile at the mask plane is shown in Fig. 7, as calculated in CodeV for a 250  $\mu\text{m}$ -diameter spherical source. It is seen that the intensity is strongest in the centre of the field and drops off towards the edges. However, since the chord length of a scan through the ring field increases with distance  $x$  away from the centre of the field, the scan integrated intensity should be constant, as discussed in Sec. 4.3. The scan integrated intensity is plotted in Fig. 7 for the two cases of using a toroid or a CPC as the reimaging mirror. It is found that the aberrations of the reimaging mirror cause the intensity to fall off at a greater rate than desired. This effect is stronger for the toroid, which has greater aberrations, and could be compensated in the design of the ripple plate.

The collection solid angle of the condenser is found from ray-tracing to be the full  $2\pi$  of a hemisphere, making optimal use of the source. The magnification of the source onto the ring-field width is less than the maximum of 24 for the 250  $\mu\text{m}$  source. If desired the  $\sigma$  of the illumination could be reduced by increasing the magnification and still allow a full  $2\pi$  solid angle to be collected. In the same way the  $\sigma$  could be increased by reducing the source magnification and under-filling the ring field. Again this would cost no loss in collection solid angle. As designed, the small stand-off distance between the parabolic collector and the source would be impractical when used with a laser-produced plasma source, due to heat load and debris that may damage the optic. This could be worked around: for example, a large ellipsoidal collector could image the source to the focus of an off-axis paraboloid which then produces a collimated beam. Alternatively, a ripple plate mirror



**Figure 7.** (a) Layout of a condenser design for a 0.25 NA camera. (b) Illumination intensity at the mask plane, for a 0.25 mm diameter spherical source and a toroidal reimaging mirror. The length scale is the same as the  $x$  axis of (c). (c) Scan-integrated intensity for a toroidal reimaging mirror (solid line) and a CPC reimaging mirror (broken line).



**Figure 8.** Pupil fill of the central field point of the condenser of Fig. 7 with a toroidal reimaging mirror, for (a) the central field point, and (b) a field point at an azimuthal angle of  $20^\circ$ .

could be designed which accepts a converging beam from an ellipsoidal collector. Using the appropriate “front-end” optics, the condenser could also be used with a synchrotron source. For an insertion-device source it may be necessary to use a ripple plate of much smaller area (and hence smaller period).

The pupil distributions at the central and edge field points are shown in Fig. 8. There is some variation across the field, in that the lines of the ripple plate appear to rotate as the field point is moved along the arc. This is a geometrical effect, due to the perspective of the channels as viewed from the direction corresponding to that particular field point. The number of vertical lines in the pupil fill is dependent on the number of periods of the ripple plate. A more uniform fill could be achieved by reducing the period from 5 mm to 1 mm, where the aberrations of the reimaging mirror blur out all trace of the vertical lines. Alternatively, the ripple plate could be dithered along the  $x$  axis to blur out the pupil fill without affecting the illumination intensity at the mask. Perhaps more troublesome is the fact that the pupil fill does not retain a circular shape across the field. This appears to be due to aberrations in the reimaging mirror, and it might be possible to improve this by optimising the shape of this mirror. Alternatively, the ripple plate reflectivity could be modified at specific places, to effectively define the condenser pupil stop for each field point.

## 6. CONCLUSIONS

A new concept, the ripple-plate condenser, has been developed to meet the requirements for illuminating an EUV ring-field projection lithography system. In the ripple plate condenser, a gently undulating surface is used to redirect a collimated beam into a beam with an arc-like angular distribution. This occurs by an analogous process to conical diffraction, and requires the collimated beam to be incident on the plate at a grazing angle, in a direction parallel to the ripples. The ripple plate defines the pupil of the condenser, and is imaged into the entrance pupil of the projection optics. The same imaging mirror that does this also focuses the arc-like angular distribution of light into an arc. Any given field point on the illumination arc receives light from positions on the ripple plate which have the right slope to direct light to that point. The correct slope occurs twice per ripple period, so the angular fill for a given field point consists of a dense array of stripes masked by the circular pupil of the ripple plate. A completely uniform fill is achieved by vibrating the ripple plate slightly. The uniformity of intensity at the illumination arc is determined by the distribution of slopes of the ripple plate. An analytic description of the ripple profile was found which gives a uniform scan-integrated intensity.

A ripple plate condenser was designed which consists of: a paraboloid collector operating at near-normal incidence, the grazing-incidence ripple plate, and a grazing-incidence toroidal imaging mirror. This condenser

was designed to illuminate a 0.25 NA projection optics system with an 8 mm ring-field width, from a 0.25 mm laser-produced plasma source, and was found to have a collection solid angle approaching a full  $2\pi$  hemisphere. Furthermore, there is no limitation on the sector angle of the illuminated arc, so large fields can be illuminated. The ripple plate undulations in the simulations presented here had a period of 5 mm and peak-to-valley amplitude of 792  $\mu\text{m}$ . Such a plate could be manufactured by diamond turning.

## ACKNOWLEDGEMENTS

The authors would like to thank Don Sweeney and Gary Sommargren for helpful discussions. This work was performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract No. W-7405-ENG-48. Funding was provided by the Extreme Ultraviolet Limited Liability Corporation under a Cooperative Research and Development Agreement.

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